

Spitzer Observations of Red Galaxies: Implication for High-Redshift Star Formation

Casey Papovich^a for the GOODS and MIPS GTO teams

^a*Spitzer Fellow, Steward Observatory, 933 N. Cherry Avenue, Tucson, AZ 85721*

Abstract

My colleagues and I identified distant red galaxies (DRGs) with $J - K_s > 2.3$ in the southern Great Observatories Origins Deep Surveys (GOODS-S) field. These galaxies reside at $z \sim 1-3.5$, ($\langle z \rangle \simeq 2.2$) and based on their ACS ($0.4-1 \mu\text{m}$), ISAAC ($1-2.2 \mu\text{m}$), and IRAC ($3-8 \mu\text{m}$) photometry, they typically have inferred stellar masses $\mathcal{M} \gtrsim 10^{11} \mathcal{M}_\odot$. Interestingly, more than 50% of these objects have $24 \mu\text{m}$ flux densities $\geq 50 \mu\text{Jy}$. Attributing the IR emission to star-formation implies star-formation rates (SFRs) of $\simeq 100-1000 \mathcal{M}_\odot \text{ yr}^{-1}$. As a result, galaxies with $\mathcal{M} \geq 10^{11} \mathcal{M}_\odot$ have specific SFRs equal to or exceeding the global value at $z \sim 1.5-3$. In contrast, galaxies with $\mathcal{M} \geq 10^{11} \mathcal{M}_\odot$ at $z \sim 0.3-0.75$ have specific SFRs less than the global average, and more than an order of magnitude lower than that for massive DRGs at $z \sim 1.5-3$. Thus, the bulk of star formation in massive galaxies is largely complete by $z \sim 1.5$. The red colors and large inferred stellar masses in the DRGs suggest that much of the star formation in these galaxies occurred at redshifts $z \gtrsim 5-6$. Using model star-formation histories that match the DRG colors and stellar masses at $z \sim 2-3$, and measurements of the UV luminosity density at $z \gtrsim 5-6$, we consider what constraints exist on the stellar initial mass function in the progenitors of the massive DRGs at $z \sim 2-3$.

Key words: Galaxies: evolution, formation, high-redshift, stellar-content,
Infrared: galaxies, Stars: initial mass function

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1 Introduction

Although as much as $\sim 50\%$ of the stellar mass in galaxies today may have formed during the short time between $z \sim 3$ and 1 (e.g. Dickinson et al., 2003; Rudnick et al., 2003), it is still unclear where these stars formed. E.g., one hypothesis is that galaxies “downsize”, with massive galaxies forming most of their stars in their current configuration at high- z , and lower mass galaxies continuing to form stars at lower- z (e.g., Cowie et al., 1999; Bauer et al., 2005; De Lucia et al., 2005; Juneau et al., 2005). Alternatively, stars may form predominantly in low-mass galaxies at high- z , which then merge hierarchically over time, slowly assembling into large, massive galaxies at more recent times (e.g., Baugh et al., 1998; Kauffmann & Charlot, 1998; Cimatti et al., 2002).

Email address: papovich@as.arizona.edu (Casey Papovich).

Massive galaxies with stellar populations older than a few megayears have recently been identified and studied with *Spitzer* as high as $z \sim 6-7$ (Eyles et al., 2005; Yan et al., 2005; Mobasher et al., 2005). One question from this is, what are the descendants of these $z \sim 6$ massive galaxies? And, perhaps more importantly (especially in the context of this meeting), what kind of stellar populations are forming in these galaxies (i.e., are there enough massive stars to produce the Lyman-continuum photons necessary to reionize the Universe)? It appears that there are too few luminous quasars at $z \gtrsim 5-6$ to provide enough global radiation for reionization (Fan et al., 2002). So, the burden now rests on early stellar generations to provide enough UV photons for reionization. It may be that there are enough small galaxies at $z \gtrsim 6$ with high UV escape fractions for this task (Yan et al., 2003), or maybe the old stellar populations in massive $z \sim 6$ galaxies supplied these photons (Panagia et al., 2005). There are as-of-yet few constraints on the stellar populations in these galaxies.

In these proceedings, I discuss recent *Spitzer* observations at (3–24 μm) of massive galaxies at $z \sim 1.5-3$ in the southern Great Observatories Origins Deep (GOODS-S) Field. The *Spitzer*/MIPS 24 μm observations provide new constraints on the SFRs in massive galaxies at these epochs. In addition, the *Spitzer*/IRAC observations at 3.6–8 μm constrain the *total* mass in old stars in galaxies at these redshifts. As I argue below, the constraints on the mass in stars from ancient stellar populations now provide crude limits on the form of the initial mass function (IMF) in galaxies near the epoch of reionization.

2 *Spitzer* Observations of the Massive Galaxies in GOODS-S

GOODS is a multiwavelength survey of two $10' \times 15'$ fields, one in the northern *Hubble* Deep Field, and one in the southern *Chandra* Deep Field. The GOODS datasets include (along with other things) *HST*/ACS and VLT/ISAAC imaging (Giavalisco et al., 2004a), and recent *Spitzer* imaging (M. Dickinson et al., in prep.). We also use data from *Spitzer*/MIPS 24 μm in the GOODS-S field from time allocated to the MIPS GTOs (Papovich et al., 2004).

From the GOODS-S datasets, my colleagues and I identified distant red galaxies (DRGs) with $J - K_s > 2.3$ mag. Franx et al. (2003) used this color criterion to identify galaxies at $z \sim 2-3.5$ that in principle have a strong Balmer/4000 Å break between the J - and K_s -bands. This color selection should be sensitive to any galaxy dominated by a passively evolving stellar population older than ~ 250 Myr at these redshifts (Franx et al., 2003). For the GOODS-S ISAAC images, the $J - K_s > 2.3$ mag selection is approximately complete to stellar mass $\mathcal{M} \geq 10^{11} \mathcal{M}_\odot$ for passively evolving galaxies. In the GOODS-S, we find 153 DRGs to $K_s \leq 23.2$ mag, spanning $0.8 \leq z \leq 3.7$, with $\langle z \rangle \simeq 2.2$. Roughly 15% of these have X-ray detections in 1 Msec *Chandra* data (Alexander et al., 2003), suggesting that many of these galaxies harbor strong AGN (see Papovich et al., 2005; L. Moustakas et al., in prep.).

Approximately 50% of the DRGs have *Spitzer* detections with $f_{\nu}(24\mu\text{m}) \geq 50 \mu\text{Jy}$. The $24 \mu\text{m}$ emission at these redshifts probes the mid-IR ($\sim 5\text{--}10 \mu\text{m}$), which broadly correlates with the total IR, $L_{\text{IR}} \equiv L(8\text{--}1000\mu\text{m})$ (e.g., Chary & Elbaz, 2001). We convert the observed $24 \mu\text{m}$ flux densities to a total IR luminosity using the Dale & Helou (2002) IR template spectral energy distributions and the measured redshifts. Some scatter is inherent in this conversion, and is typically a factor of 2–3 in L_{IR} (e.g., Chapman et al., 2003). We therefore adopt a 0.5 dex uncertainty on L_{IR} , which also includes an uncertainty arising from redshift errors (see Papovich et al., 2005). For the DRGs at $z \sim 1.5\text{--}3$, the $24 \mu\text{m}$ flux densities yield $L_{\text{IR}} \approx 10^{11.5\text{--}13} L_{\odot}$, which if attributed to star-formation corresponds to SFRs of $\approx 100\text{--}1000 M_{\odot} \text{ yr}^{-1}$ (Kennicutt, 1998; Bell, 2003). Thus, a substantial fraction of massive galaxies at these redshifts are involved in intense starbursts. A similar conclusion is reached for *BzK*-selected galaxies at $z \sim 1.9$ in the northern GOODS field (Daddi et al., 2005).

3 Stellar Populations and SFRs in High- z Massive Galaxies

We modeled the DRG stellar populations by comparing their ACS, ISAAC, and IRAC photometry to a suite of stellar-population synthesis models (Bruzual & Charlot, 2003), varying the age, star-formation history, and dust content. We use the model stellar-mass-to-light ratios to estimate the galaxies’ stellar mass. We first allow for star-formation histories with the SFR parameterized as a decaying exponential with an e -folding time, τ , ranging from short τ ’s (burst of star-formation) to long τ ’s (constant star-formation). We also use models with a two-component star-formation history characterized by a passively evolving stellar population formed in a “burst” at $z_{\text{form}} = \infty$, summed with the exponentially-decaying-SFR model above. The two-component models check the effects of discrete bursts. Figure 1 shows examples of fitting these models to a DRG with an apparent 4000 \AA /Balmer break between the J - and K_s -bands. The two panels in the figure show the best-fitting models for the one- and two-component models described above. Although the modeling loosely constrains the ages, dust content, and star-formation histories of the DRGs, it provides relatively robust estimates of the galaxies’ stellar masses (Papovich et al., 2005, see also Förster-Schreiber et al., 2004). In the DRG in figure 1, even though the star-formation histories are quite different, the derived stellar mass is nearly identical. Typical uncertainties for the stellar masses for the full DRG sample are 0.1–0.3 dex.

Figure 2 shows the specific SFRs (Ψ/M) derived from the masses and SFRs of the DRGs, where the SFRs are calculated from the summed UV and *Spitzer* IR emission (Bell et al., 2005). The figure also shows the specific SFRs for galaxies at lower redshift in the COMBO-17 survey (Wolf et al., 2003), which overlaps with the GTO *Spitzer* imaging at $24 \mu\text{m}$. The SFRs for the COMBO-17 galaxies are calculated using the MIPS $24 \mu\text{m}$ imaging and rest-frame UV emission in an analogous manner as for the DRGs. Masses for COMBO-17 galaxies were estimated from their rest-frame $M(V)$ and $U - V$ colors, and

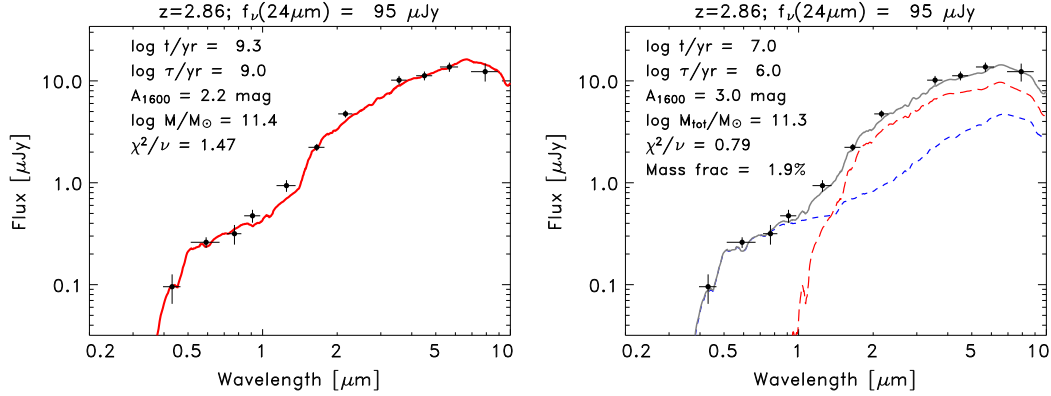


Fig. 1. Illustration of fitting SED models to one of the GOODS-S DRGs which has an indication of both young and old stellar populations. *LEFT*: the best-fit model with the star-formation history parameterized as a monotonic, decaying exponential with best-fit e -folding time $\tau=10^9$ yr. *RIGHT*: the best-fit model where the star formation history consists of two components, a single burst at $z=\infty$, representing previously formed stellar populations, summed with a monotonic, decaying exponential with best-fit e -folding time $\tau=10^6$ yr, representing any ongoing star formation. The dashed curves in the right panel show the contribution from each of the two model components. The inset gives the best-fit model parameters. The data points show the ACS $B_{435}V_{606}i_{775}z_{850}$, ISAAC JHK_s , and IRAC 3.6–8.0 μm photometry and errors.

have a typical uncertainty of 0.3 dex (see Bell et al., 2004, 2005).

Although the sample is biased against galaxies with low stellar masses (and thus specific SFRs); the data are sensitive to all galaxies with larger stellar masses. At $z\sim 0.3\text{--}0.7$, there is an apparent lack of galaxies with high specific SFRs and high stellar masses. In contrast, the massive DRGs at $1.5\leq z\leq 3$ have much higher specific SFRs for galaxies. Quantitatively, the DRGs with $\mathcal{M}>10^{11} \mathcal{M}_\odot$ and $1.5\leq z\leq 3$ have $\Psi/\mathcal{M}\sim 0.2\text{--}10 \text{ Gyr}^{-1}$, with a mean value of $\sim 2.4 \text{ Gyr}^{-1}$ (excluding X-ray sources). By $z\sim 0.7$ (0.4) galaxies with $\mathcal{M}\geq 10^{11} \mathcal{M}_\odot$ have $\Psi/\mathcal{M}\sim 0.1\text{--}1$ ($\lesssim 0.5$) Gyr^{-1} , an order of magnitude lower than for the massive DRGs. We define the integrated specific SFR as the ratio of the sum of the SFRs, Ψ_i , to the sum of their stellar masses, \mathcal{M}_i , $\Upsilon\equiv\sum_i \Psi_i/\sum_i \mathcal{M}_i$, summed over all i galaxies. This is essentially just the ratio of the SFR density to the stellar mass density for a volume-limited sample of galaxies. Figure 3 shows the integrated specific SFRs for DRGs at $z\sim 1.5\text{--}3.0$ and COMBO-17 at $z\sim 0.4$ and 0.7 with $\mathcal{M}\geq 10^{11} \mathcal{M}_\odot$. The data point for the DRGs includes all objects with $\mathcal{M}\geq 10^{11} \mathcal{M}_\odot$, assuming that 24 μm -undetected DRGs have $f_\nu(24\mu\text{m}) = 60 \mu\text{Jy}$, and excluding objects with X-ray detections of IR luminosities of color indicative of AGN (see Papovich et al. 2005). The upper bound of the error box shows what happens if we include those objects with possible AGN. The bottom bound of the error box shows what happens if we continue to exclude objects with possible AGN, but assuming that the 24 μm -undetected DRGs have no star formation. The integrated

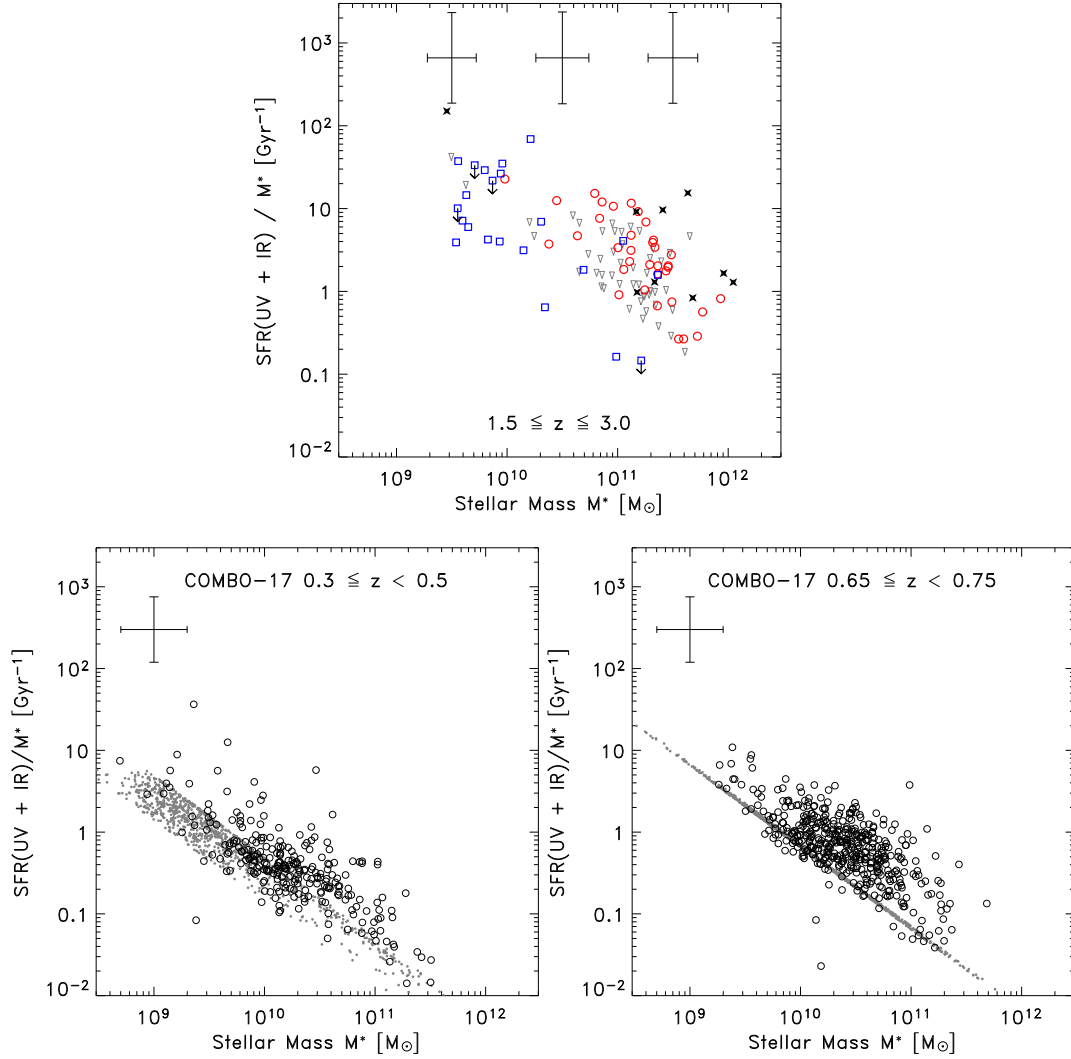


Fig. 2. Galaxy stellar mass versus specific SFR. The top panel shows the DRGs (red circles, grey triangles denote upper limits, black stars indicate X-ray DRGs) and galaxies from the HDF-N (blue squares; see Papovich et al., 2005), restricted to $1.5 \leq z \leq 3.0$. The bottom panels show COMBO-17 galaxy samples at lower-redshift (as labeled). Open circles show $24 \mu\text{m}$ -detected galaxies; small filled circles show upper limits. Mean uncertainties are indicated as a function of stellar mass.

specific SFR in galaxies with $\mathcal{M} > 10^{11} \mathcal{M}_{\odot}$ declines by more than an order of magnitude from $z \sim 1.5-3$ to $z \lesssim 0.7$. This downward evolution in the specific SFRs seems to support the so-called “downsizing” paradigm. Our results indicate that star-formation in massive galaxies is reduced for $z \lesssim 1$ as galaxies with lower stellar masses have higher specific SFRs.

Figure 3 also shows the specific SFR integrated over all galaxies (not just the most massive); this is the ratio of the cosmic SFR density (from Cole et al., 2001) to its integral, i.e., $\Upsilon = \dot{\rho}_* / \int \dot{\rho}_* dt$. The global integrated specific SFR

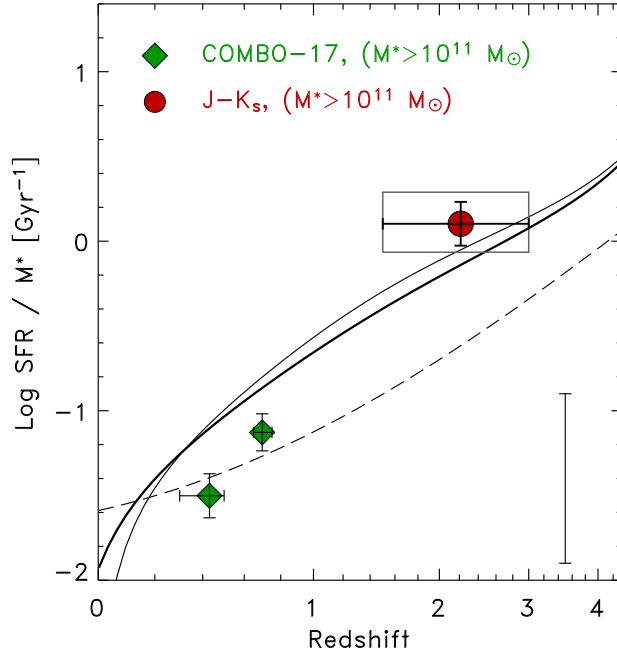


Fig. 3. Evolution of the integrated specific SFR, i.e., the ratio of the total SFR to the total stellar mass (from Papovich et al., 2005). The curves show the expected evolution of the ratio of the total SFR to the total galaxy stellar mass densities from an empirical fit to the evolution of the SFR density (solid lines, thick line includes correction for dust extinction; Cole et al., 2001), and the model of Hernquist & Springel (dashed line; 2003). The data points show results for galaxies with $\mathcal{M}^* \geq 10^{11} \mathcal{M}_\odot$. The filled diamonds show the mean values derived for COMBO-17 galaxies, and the filled circle shows the mean value for the DRGs. The box about the DRG point shows how the results change based on some various assumptions (see text; Papovich et al. 2005). The error bars do not include systematic uncertainties in the SFRs, which are indicated by the inset error bar.

declines steadily with decreasing redshift, i.e., there is a decrease in the global specific SFR. The evolution in the integrated specific SFR in massive galaxies is accelerated relative to the global value. Galaxies with $\mathcal{M} \geq 10^{11} \mathcal{M}_\odot$ were forming stars at or slightly above the rate integrated over all galaxies at $z \sim 1.5-3$. In contrast, by $z \lesssim 1$ galaxies with $\mathcal{M} \geq 10^{11} \mathcal{M}_\odot$ have an integrated specific SFR much lower than the global value. Thus, by $z \lesssim 1.5$ massive galaxies have formed most of their stellar mass, and lower-mass galaxies dominate the cosmic SFR density (see further discussion in Papovich et al., 2005).

4 Old Stellar Populations in Massive Galaxies at $2 < z < 3$: Implications for the IMF at Higher Redshift

Because the DRGs have red colors, the model fits favor stellar-population ages of 1–2 Gyr. This implies that the earliest DRG progenitors formed at $z \gtrsim 5-6$, possibly accounting for much of their stellar mass (Förster-Schreiber et al.,

2004; Papovich et al., 2005). Owing mostly to model degeneracies, the uncertainties on galaxy ages, dust content, and star-formation histories from the stellar-population modeling can be more than an order of magnitude (e.g., Papovich et al., 2001). Nonetheless, with the model star-formation histories and stellar masses of galaxies at $z \sim 2-3$, we can set some broad statistical constraints on the SFRs of galaxies at $z \gtrsim 5-6$. For example, Ferguson et al. (2002) analyzed the model star-formation histories of LBGs at $z \sim 2-3$, and concluded that in order for the progenitors of these galaxies to produce enough Lyman-continuum photons to reionize the Universe requires that the stellar populations form from an IMF heavily weighted toward high-mass stars, and/or an episodic SFR. Förster-Schreiber et al. (2004) found that if the DRGs had a constant SFR over their lifetimes, then integrated UV-luminosity density from the DRG progenitors decreases by a factor of ≈ 2 from $z \sim 2$ to 6.

It is interesting to ask what the stellar-population models imply for the luminosities of the progenitors of the GOODS-S DRGs at $z \gtrsim 3-5$. Figure 4 shows the past SFR for the DRG in figure 1 for the best-fitting models using the two different star-formation histories (see § 3, figure 1). The dashed line shows the past UV luminosity for the model with a monotonically evolving SFR. The solid line shows the past SFR for the model with two star formation components. One component is a monotonically evolving “burst”, which in the case of this figure is a very short, recent burst (causing the spike at $z \simeq 3$). The second component represents a burst of star formation in the past, averaged over the time since the Big Bang. A galaxy with two “bursts” of star-formation would simply show two spikes in figure 4. If we consider this model as a proxy for the history of all galaxies, then the star-formation history in the figure represents the maximal rate of star formation due to stochastic bursts as a function of redshift for an individual galaxy (see Ferguson et al. 2002).

Figure 5 shows the integrated past UV luminosity density (a proxy for the SFR) for all the GOODS-S DRGs with $2 < z < 3$ and $\mathcal{M} \geq 10^{11} \mathcal{M}_{\odot}$. For these redshifts and stellar mass the sample is approximate complete (i.e., nearly volume limited) for passively evolving galaxies. The figure also shows instantaneous measurements of the UV luminosity density at $z \sim 3-6$ from Steidel et al. (1999) and Giavalisco et al. (2004b) using LBGs. Comparing the measured UV luminosity density to what we infer from the past output from the DRGs, if the massive DRGs at $2 < z < 3$ formed their stellar populations with a monotonically evolving SFR, then they account for $< 5\%$ of the $z \sim 6$ UV luminosity density. However, if these galaxies instead form stars in quasi-stochastic bursts throughout their lifetime, then they account for $\approx 10-15\%$ of the $z \sim 6$ UV luminosity density. Inverting that statement, roughly 10–15% of the stars formed in $z \sim 6$ galaxies end up in massive DRGs at $2 < z < 3$.

We can go one step further and impose the constraint that the stars forming at $z \sim 6$ can not *overproduce* the stellar mass at $z \sim 2-3$. In this case the

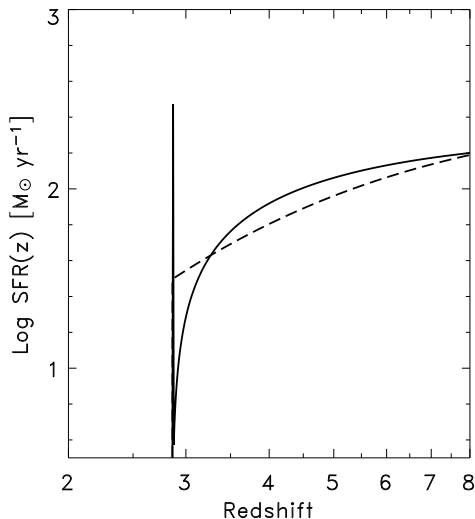


Fig. 4. Past SFR for the DRG at $z=2.9$ illustrated in figure 1. The dashed line shows the past SFR for the model with a monotonically evolving SFR, $\Psi(t) \sim \exp(-t/\tau)$. The solid line shows the past SFR of a two-component model. One component is a recent “burst”, modeled as a decaying exponential with a short age and e-folding time. The other component approximates the average star-formation history of a “burst” sometime in the past between $z=2.9$ and $z \sim \infty$.

data allow us to place a very loose constraint on the IMF of the old stellar populations in the DRGs. If the past IMF in these galaxies is weighted to high-mass stars (e.g., with a slope shallower than Salpeter, $x < 1.35$), then one gets more UV photons produced for a given amount of formed stellar mass (more “bang for the buck”). The rate that the light from a stellar population fades goes as $L_B(t) \sim t^{-\alpha}$. We approximate the change in the past UV luminosity for a varying IMF by scaling the past UV luminosity by the change in B -band luminosity. For a Salpeter IMF $\alpha = 0.8$, whereas a “Flat” IMF (with slope $x=0.0$) has $\alpha = 1.4$. If the old stellar populations formed with a top-heavy ($x=0.0$), flat IMF, then the past UV luminosity density is $\sim 90\%$ of the $z \sim 6$ Giavalisco et al. (2004b) value. If the measured $z \sim 6$ UV luminosity density is in fact lower, then the stellar mass in the DRGs can account for all (Bouwens et al., 2005), or more (Bunker et al., 2004) than what can be formed with a $x=0.0$ IMF. Therefore, if the UV luminosity density is lower than the Giavalisco et al., (2004b) value, then the IMF *must* have a slope $x > 0.0$ to avoid the awkward situation that the $z \gtrsim 6$ galaxies overproduce the stellar mass in DRGs with $2 < z < 3$ and $\mathcal{M} \geq 10^{11} \mathcal{M}_\odot$.

Such a situation seems extreme. It is possible that the massive DRGs contain a large amount of the stars formed at $z \sim 6$. Currently, we have only the limited constraint that the slope of the IMF of the $z \sim 6$ star-forming galaxies is $x > 0.0$. This may be tightened as the observations of the $z \gtrsim 6$ UV luminosity density improve (or we decrease the uncertainty in the stellar-population modeling).

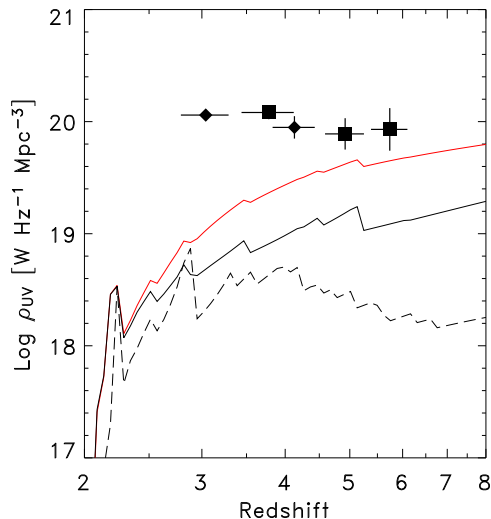


Fig. 5. Integrated UV luminosity density from the past best-fit star-formation histories of all DRGs with $2 < z < 3$ and $\mathcal{M} \geq 10^{11} \mathcal{M}_{\odot}$. The dashed line shows the past UV luminosity density for the single-component star-formation histories; the solid line shows the two-component models. Both of the black lines correspond to stellar populations formed with a Salpeter IMF, with slope $x=1.35$. The red line indicates the past UV luminosity density for the two-component models, and an IMF weighted to high-mass stars, with $x=0.0$. Data points are from Steidel et al. (1999; diamonds), and Giavalisco et al. (2004; squares).

Moreover, the constraint will be better if we can measure the UV luminosity density at yet higher redshift. For example, Bouwens et al., (2004) suggest that the $z \sim 7-8$ UV luminosity density is lower than at $z \sim 6$ by an order of magnitude. In this case, based on figure 5 we may already be able to discard an IMF with a very shallow slope. We may yet achieve indirect constraints on the IMF of high-redshift galaxies at the epoch of reionization using the old stellar populations we find at “low” redshifts, $z \sim 2-3$.

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